Response by the Authors to S. R. Hencher's Discussion of the Paper "Comparison of Different Techniques of Tilt Testing and Basic Friction Angle Variability Assessment

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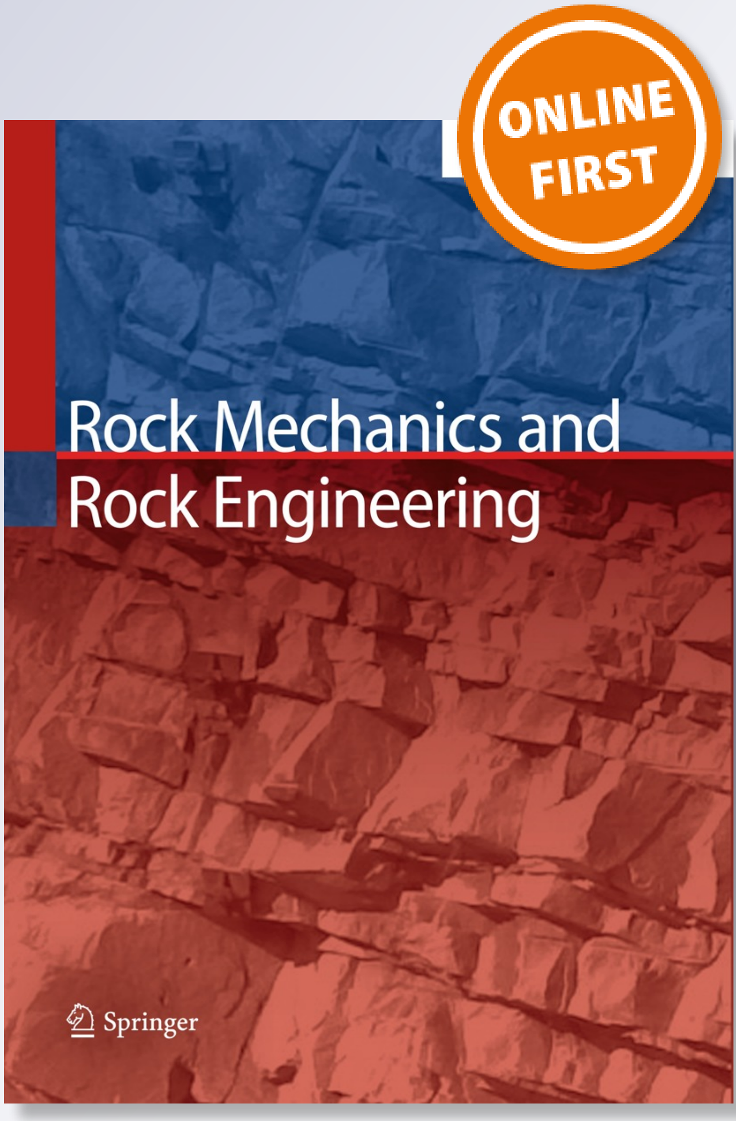

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REPLY

Response by the Authors to S. R. Hencher's Discussion of the Paper "Comparison of Different Techniques of Tilt Testing and Basic Friction Angle Variability Assessment

Leandro R. Alejano · Javier González · José Muralha

In a recent publication (Alejano et al. 2012), some issues concerning the evaluation of the basic friction angle ϕ_b of saw-cut rock surfaces were addressed. In his discussion, S.R. Hencher provides a series of useful references with some low values for the basic friction angle, refers to the variability of this parameter and puts forward a series of comments regarding the paper.

The authors would like to acknowledge S.R. Hencher's interest in the paper and thank him for extending the scope of the research and for providing the opportunity to present these additional comments, clarify some aspects of the work and highlight some of the main conclusions.

The main aim of the author's work was to facilitate the laboratory estimate of ϕ_b to input a reliable value in the formulation of Barton's peak shear strength criterion. As stated in the first paragraph of the introduction to the paper, it is important to note that this criterion applies to natural unfilled rough rock joints. A priori it therefore does not apply to filled discontinuities or to those that have suffered previous shear (typically mismatched), where polished or slicken-sided surfaces appear and where flour rock or fill can be encountered.

Concerning the variability of ϕ_b, it is important to note that the tilt tests presented in the paper were performed using samples from the same rock types. Moreover, tilt tests were performed using the lateral surfaces of prismatic samples cut from the same rock block. So, the standard deviation values presented in the paper only take into account the intrinsic variability of this kind of test.

Tilt tests for the evaluation of ϕ_b and the remaining index tests for the characterization of rock joint shear strength proposed by Barton (1999) are very simple and straightforward. As a consequence, inexperienced designers may overlook the variability in the resulting basic friction angles and this, in turn, may lead to hazardous safety assessments.

It should also be stressed that the dispersion of the empirical equations that support Barton's peak shear strength criterion has always been mentioned, from the earliest works to present days (Barton and Choubey 1977; Barton 2011).

The paper presents results of tilt tests that rendered low basic friction values. Such low values of ϕ_b are generally provided by unweathered rocks with high compressive strength (e.g., in excess of 150 MPa). These low friction values should be anticipated, as saw-cut surfaces and cores of these rocks often show very smooth and sometimes polished surfaces.

In the particular case of porphyritic granite, the values displayed in Fig. 1 of the paper refer to all tilt tests repetitions performed with all possible combinations of the lateral faces (120 mm long and 45 mm wide) of two prismatic blocks, resulting in 384 values corresponding to 3 repetitions × (8 × 8 combinations) × 2 tilting directions. To address the issue of the low ϕ_b values, it is preferable to study just the result of each tilt test, considering this as the median of the three repetitions. These values, presented in Fig. 1, show clearly that around 50 % of the values are below 20°. In fact, the median is exactly 19°, the mean (arithmetic) of the friction angles is 19.2° and the standard deviation is 4.46°.

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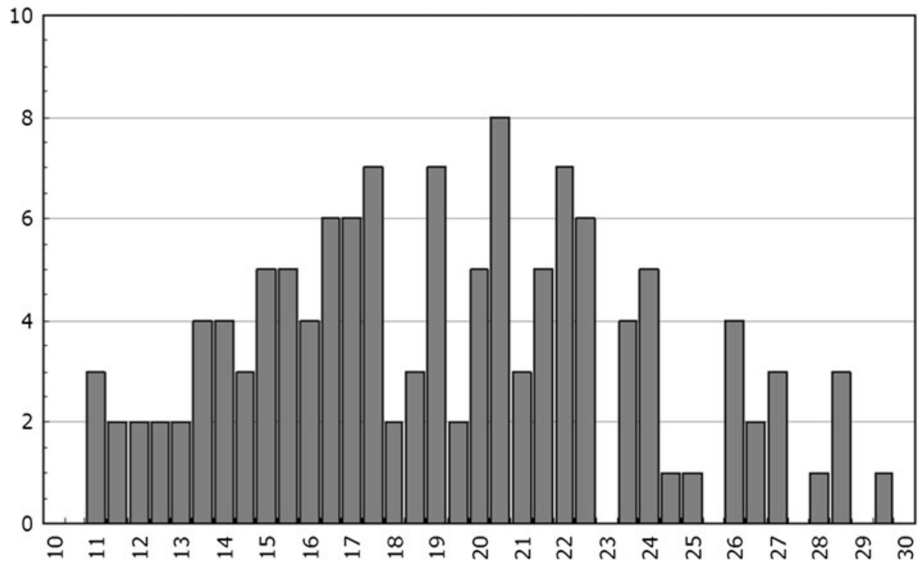
Fig. 1 Histogram of the basic friction angles of tilt tests performed on the lateral sides of porphyritic granite prismatic blocks



Compared with other results taken from literature reviews, namely those compiled by Barton and Choubey (1977), these values have to be considered low. However, it is a qualitative characterization that is always related to the objectives for which the values of ϕ_b are going to be used. Frequently, this objective is the evaluation of the residual friction angle ϕ_r of Barton's shear strength criterion.

$$\phi_r = (\phi_b - 20) + 20\frac{r}{R}\text{(friction angles in degrees)} \qquad (1)$$

This equation reflects the idea that the residual friction angle is the basic friction angle in the case of an unweathered rock joint and the Schmidt rebound on the joint walls r is equal to the rebound on a saw-cut surface R; in general, however, it is ϕ_b reduced by a certain amount proportional to r/R that depicts the alteration of the walls of natural weathered joints. Looking at the equation under this rationale leads to the conclusion that ϕ_b values lower than 20° should not be foreseen, and that this value can be envisaged as a reasonable lower bound for the basic friction angle. Though Eq. (1) can mathematically still be used with ϕ_b values lower than 20°, it may not be applicable to fresh, clean unweathered joints in hard competent rock.

The low basic friction angle values presented in the paper stressed the need to further investigate the effect of surface finishing on the results of tilt tests used to estimate ϕ_b. Aiming at standardizing the tilt test, but bearing in mind that it is intended to be a simple and practical test, a series of tests is being performed by the authors with the objective of studying the effects of surface finishing and establishing a common procedure for preparing the surfaces.

In these tests, a 50 mm thick slab of dimensioned stone (nepheline syenite) was used. One surface of the slab was polished, while the opposite surface was sand sawn producing a texture with a uniform roughness smaller than 0.5 mm. The slab was cut with a saw disk into prismatic blocks with a 50 mm side square cross section, so that the four lateral surfaces of these prismatic blocks had a polished surface, a rough surface and two smooth saw-cut surfaces.

Table 1 Basic friction angle for different surface finishes

Surface finishing	Range (°)	Median (°)	Average (°)*
Polished	9.5–20.0	11	11.6
Saw-cut	20.5–29.0	27	26.2
Rough	26.5–33.0	31	30.6

* Average of the friction angles, discarding the two highest and the two lowest values

A few tilt tests have already been performed (11 from each type of surface finish). Preliminary results, presented in Table 1, reveal that the difference between the saw-cut and the rough sand-sawed surfaces is not as relevant as could be expected. They also allow the conclusion that tilt tests to estimate ϕ_b should not be performed when the saw-cut rock surfaces show any kind of polishing.

Since it can be expected that a small increase in the normal stress (e.g., up to 10 kPa) may lead to a decrease in the dispersion of the results, the ongoing research will also try to establish a procedure for determining the basic friction angle using tilt tests or other low normal stress tests (like pull or push tests). Performing both types of tests on the same samples will allow a direct comparison of the results. Using different types of igneous, metamorphic and sedimentary rocks, special attention is also being given to the preparation of the surfaces and how the rock lithology, hardness and grain size can influence the surface finish.

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